CLINICAL RESEARCH STUDIES

From the Society for Vascular Surgery

Magnetic resonance angiography of collateral blood supply to spinal cord in thoracic and thoracoabdominal aortic aneurysm patients

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Objective: **Preservation of spinal cord blood supply during descending thoracic (TAA) and thoracoabdominal aortic aneurysm (TAAA) surgery is mandatory to prevent neurologic complications. Although collateral arteries have been identified occasionally and are considered crucial for maintaining spinal cord function in the individual patient, their critical functionality is poorly understood and very little experience exists with visualization. This study investigated whether the preoperative and postoperative presence or absence of collateral arteries detected by magnetic resonance angiography (MRA) is related to spinal cord function during the intraoperative exclusion of the segmental supply to the Adamkiewicz artery.**

Methods: **Spinal cord MRA was used to localize the Adamkiewicz artery and its segmental supplier in 85 patients scheduled for open elective surgery for TAA or TAAA. The segmental artery to the Adamkiewicz artery was inside the cross-clamped aortic area in 55 patients, and spinal cord supply was consequently dependent on collateral supply. In these 55 patients the presence of collaterals originating from arteries outside the cross-clamped aortic segment was related to changes in the intraoperative motor-evoked potentials (MEPs) that occurred before corrective measures. Twenty-one patients returned for postoperative MRA.**

Results: **A highly significant ($P < .0015$) relation was found between the presence of collaterals and intraoperative spinal cord function. In 30 of 31 patients (97%) in whom collaterals were identified, MEPs remained stable. The collaterals in most patients originated caudally to the distal clamp (eg, from the pelvic arteries), which were perfused by means of extracorporeal circulation during cross-clamping. The MEPs declined in 9 of 24 patients (38%) in whom no collaterals were preoperatively visualized. Postoperatively, the 21 patients who had MRA, including 10 in whom preoperatively no collaterals were found, displayed a well-developed collateral network.**

Conclusion: **Collateral arteries supplying the spinal cord can be systematically visualized using MRA. Spinal cord blood supply during open aortic surgery may crucially depend on collateral arteries. Preoperatively identified collateral supply was 97% predictive for stable intraoperative spinal cord function. Patients in whom no collaterals can be depicted preoperatively are at increased risk for spinal cord dysfunction. (J Vasc Surg 2008;48:261-71.)**

Collateral arteries are thought to contribute to the blood supply of the spinal cord in patients with extensive aortic aneurysms. Particularly in patients with extensive degenerative aortic aneurysms, most of the intercostal and lumbar arteries are occluded by plaque or thrombus, and spinal cord perfusion is assumed to depend on a collateral network, including pelvic and lumbar circulation.[1-4] The functional predictive value and the surgically relevant anatomic origins of the collateral arteries remain unresolved.

During surgical intervention for descending thoracic aortic aneurysms (TAAs) and thoracoabdominal aortic aneurysms (TAAAs), large parts of the diseased aorta are cross-clamped and the blood supply to the spinal cord may be interrupted, possibly causing ischemic spinal cord injury. Adjunctive measures to reduce the risk of paraplegia include reattachment of intercostal arteries, cerebrospinal fluid (CSF) drainage, and distal aortic perfusion. However, some experts debate the relevance of time-consuming revascularization procedures because collateral arterial networks may fully substitute for the impaired blood supply.[3,5]

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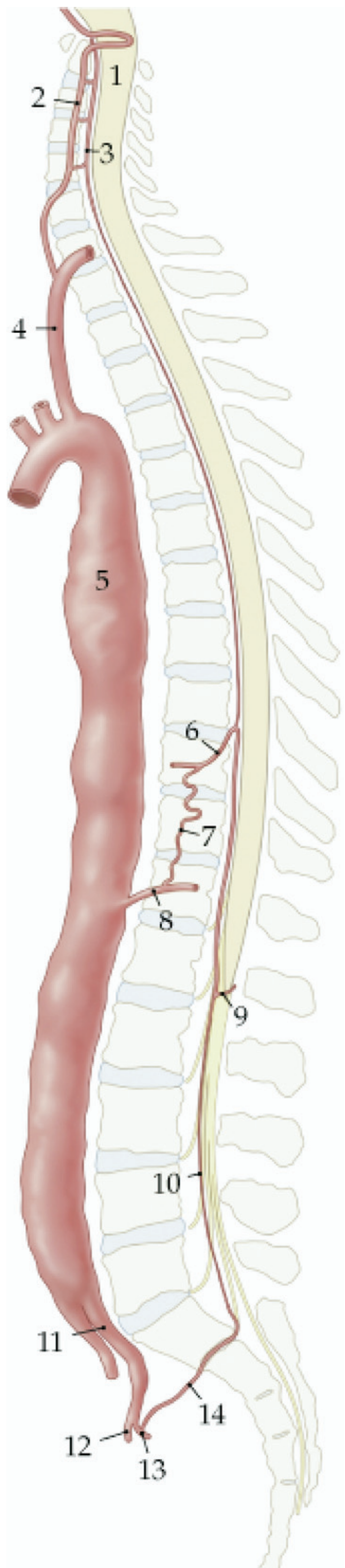


Preoperative information on the location of the most important arteries supplying blood to the spinal cord is suggested to help to reduce the incidence of neurologic deficits.[6,7] More in particular, clinically it would be relevant to know in advance which patients do and do not have a collateral network that may provide sufficient blood supply to the spinal cord to determine the risk for loss of spinal cord function during surgery.

In general, the Adamkiewicz artery is considered the most important supplier of the thoracolumbar spinal cord and therefore, theoretically, needs to be preserved during surgery. Fig 1 displays an anatomic overview of the spinal cord blood supply. The Adamkiewicz artery was shown to be still functionally patent in TAA and TAAA patients,[8] although its direct supplying intercostal or lumbar (ie, segmental) artery may be occluded due to atherosclerotic plaques or thrombus.

Even in healthy men, however, the normal blood supply to the anterior thoracolumbar spinal cord is variable and usually consists of other routes as well, including the vertebral arteries, iliolumbar arteries, and even transverse anastomoses from the posterior spinal arteries.[9,10] Owing to the atherosclerotic occlusions, existing arterial routes may become dysfunctional and collateral circulation may importantly contribute. The collateral supply in TAA and TAAA patients may consist of (1) novel proximal intersegmental collateral arteries[8,11] or (2) more remote collaterals originating from the lumbar or pelvic circulation, or both.[12] However, it remains a priori unknown whether the blood supply to the spinal cord from these additional normal or developed collateral routes is sufficient in case the supply through the Adamkiewicz artery is excluded by aortic cross-clamps, despite retrograde aortic perfusion providing blood flow to the arteries distal to the cross-clamp.

The main objective of this study was to determine whether collateral arteries functionally contribute to the spinal cord blood supply. We therefore compared the location of the Adamkiewicz artery and collateral blood supply with intraoperative spinal cord function as assessed by motor evoked

Fig. 1. Anatomic drawing shows the different blood-supplying trajectories to the thoracolumbar spinal cord in thoracoabdominal aortic aneurysm patients. The segmental artery directly connecting to the Adamkiewicz artery is partially occluded. The Adamkiewicz artery is supplied by a proximal intersegmental collateral, which originates from a segmental artery two vertebral levels below. This trajectory does not represent the only route for the blood to reach the spinal cord. Alternative original trajectories include the anterior radiculomedullary arteries deriving from the vertebral arteries and the filum terminale artery originating from the iliolumbar artery. *1*, Spinal cord; *2,* vertebral artery; *3,* anterior spinal cord; *4,* left subclavian artery; *5,* aneurysmatic aorta; *6,* Adamkiewicz artery; *7,* intersegmental collateral; *8,* segmental artery indirectly supplying the Adamkiewicz artery; *9,* anastomotic loop to the posterior spinal artery; *10,* filum terminale artery; *11,* common iliac artery; *12,* external iliac artery; *13,* internal iliac artery (hypogastric artery); *14,* iliolumbar artery.

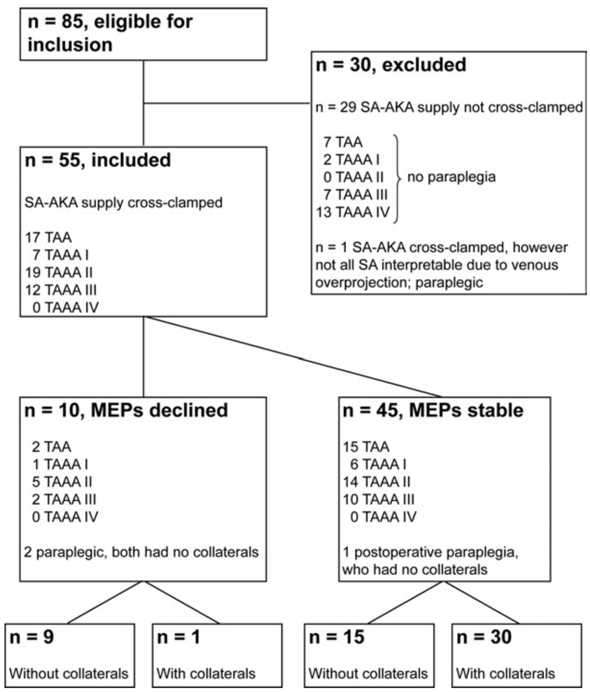


Fig 2. This flow chart shows the classification of the patients in different groups. *AKA,* Adamkiewicz artery; *MEPs,* motor-evoked potentials, *SA,* segmental artery; *TAA,* thoracic abdominal aneurysm; *TAAA,* thoracoabdominal aortic aneurysm.

potentials (MEPs). For this purpose we developed and applied small-artery magnetic resonance angiography (MRA). We hypothesized that when the collateral spinal cord blood supply is essential, postoperative TAA and TAAA patients should present a more extensive collateral network compared with the preoperative circulation because many segmental arteries are usually not revascularized.

MATERIAL AND METHODS

Patients. From Sept 2002 to Dec 2006, 85 patients (54 men and 31 women) with a mean age 65 of years (range, 32-74 years) who had a TAA or TAAA presented for elective open aortic aneurysm surgery were included for preoperative MRA. This series was not consecutive because of several logistic reasons not allowing MRA at the time of admission (urgent/emergency procedures). During the same period, 188 patients with TAA or TAAA underwent surgical treatment.

Fig 2 provides the flow chart for the preoperatively imaged and subsequently operated on patient groups. Thirty patients (35%) were not considered for the functionality analysis of the collateral supply because the segmental artery directly connecting to the Adamkiewicz artery was not excluded by aortic cross-clamping during surgery. Accordingly, the intraoperative MEP monitoring did not signal any (temporal) spinal cord dysfunction in these 30 patients. For the remaining 55 patients, in whom the segmental supply to the Adamkiewicz artery was excluded from direct aortic circulation, the relation between intraoperative MEP responses was correlated with the presence or absence of collateral arteries. In this group, 37 (67%) had advanced atherosclerotic disease and 18 (33%) had a post-type B dissection aneurysm with moderate atherosclerosis.

For postoperative MRA, 21 (15 with advanced atherosclerosis and 6 with chronic type B dissection) of the 55 patients included were also imaged 13.5 ± 9.4 months after aortic surgery. The patients in this postoperative group had undergone repairs for 10 TAAs, 3 TAAAs type I, 7 TAAAs type II, 1 TAAAs type III, and 0 TAAAs type IV. The postoperative MRA examinations were performed in a lower number of patients to demonstrate the potential effect of change in collateralization in the group of TAA and TAAA patients and because there was no direct clinical benefit for the patient. Also, the availability of the patients for follow-up was limited.

The Medical Ethics Committee of Maastricht University Hospital approved the protocol. Written informed consent was obtained from all patients before their inclusion.

Magnetic resonance angiography. All patients underwent preoperative MRA to localize the Adamkiewicz artery and its segmental supplier. The exact same imaging protocol was used for preoperative and postoperative MRI. Imaging was performed on a clinical 1.5-Tesla MRI system (Philips Intera; Philips Medical Systems, Best, The Netherlands) equipped with a phased-array spine coil. Small artery visualization was optimized by subtraction of noise-reduced precontrast images. Before contrast administration of 0.3 mmol/kg gadolinium diethylenetriamine pentaacetic acid (Schering, Berlin, Germany) intravenously injected at 3 mL/s, the three-dimensional angiographic pulse sequence (T1 weighted, fast spoiled gradient-recalled echo imaging; repetition time, 8 ms; echo time, 2 ms; flip angle, 35°; acquisition voxel sizes, 0.8 × 0.8 × 1.2 mm) was repeated four times, averaged, and the images were finally subtracted from the contrast-enhanced images.

Contrast-enhanced MRA consisted of two consecutive dynamic phases. A centric k-space filling scheme synchronized to the arrival of the contrast agent (dose, 0.3 mmol gadolinium/kg) was used to suppress the venous blood signal. The acquisition of two dynamic phases allowed differentiation between the Adamkiewicz artery and the similarly shaped outlet vein (ie. great anterior radiculomedullary vein) based on temporal intensity changes of the two dynamic phases (Fig 3). Details of the imaging protocol have been described elsewhere.[13,14]

Image analysis. Contrast-enhanced images were first postprocessed using curved multiplanar reformation. One experienced image creator determined the level and side of the Adamkiewicz artery and its segmental supplier. When the segmental artery directly connecting to the Adamkiewicz artery was (partially) occluded at its origin in the aortic wall, the nearest open segmental artery with an intersegmental connection to the directly connecting segmental artery was suggested to be the segmental supplier of the Adamkiewicz artery. Before the operation, the localization of the direct segmental supplier or, in case this was

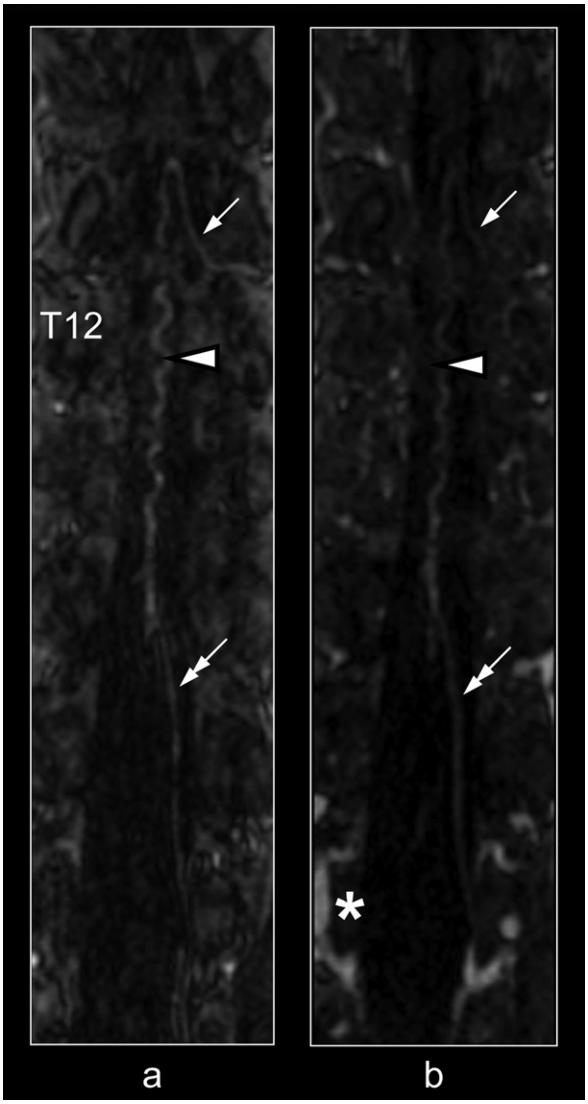


Fig 3. Curved multiplanar reformation of a contrast-enhanced magnetic resonance angiographic examination consisting of two consecutive dynamic phases illustrates the identification of the Adamkiewicz artery *(single arrow)* and the great anterior radiculomedullary vein *(double arrow)*. Note that the signal intensity of the Adamkiewicz artery relatively decreases from the **(a)** first to the **(b)** second dynamic phase, while the filling of the vein becomes more complete. The midline vasculature *(arrow head)* resembles the spatially unresolved combination of the anterior spinal artery and the anterior median vein. Note that the venous plexus *(*)* enhances only in the second-phase image.

occluded, the nearest open indirect segmental artery to the Adamkiewicz artery was reported to the surgeon.

To determine the presence of collateral arteries, two sagittal maximum-intensity projections were made from the subtracted images for the volumes on each side of the vertebral column. The original subtraction images and the maximum-intensity projections were used to identify collateral arteries that originated from vessels outside the cross-clamped aortic region and connected to the segmental supply of the Adamkiewicz artery. Images were analyzed for collateral arteries in random order to avoid learning bias. So, before surgery no information on collateralization was reported to the surgeon. Image analysis took 30 to 60 minutes for each MRA examination.

Surgical protocol. The surgical procedure was performed in manner similar to that described elsewhere.[12,15] The applied spinal cord protection protocol consisted of CSF drainage, left atrium–femoral artery or femoral artery–femoral vein bypass enabling distal aortic perfusion, and spontaneous cooling to 32°C to 33°C with active rewarming at the end of the procedure. For all patients, the aortic cross-clamp positions, subsequent MEP signals, localization of open (ie, back-bleeding) segmental arteries, and revascularization or oversewing of segmental arteries were documented during the operation and written in the operation report. The surgeon determined the level of the clamp by counting vertebral bodies with reference to the vertebral level T12.

For intraoperative monitoring of the spinal cord function, the surgical team relied on MEPs.[12] In general, the aorta was sequentially cross-clamped, thus allowing stepwise exclusion of aortic segments and assessment of changes in MEP amplitudes. When the MEP amplitude declined >50% of its original value, the spinal cord was considered to be partially ischemic because the MEP amplitude reflects the amount of firing, hence, intact alphamotoneurons. If after placement of the proximal clamp the MEPs decreased, the mean distal aortic perfusion pressure was increased until the MEPs normalized. However, if the MEPs rapidly decreased during aortic cross-clamping and were not correctable with increasing distal and mean arterial pressure, thus indicating that the excluded aortic segment contained crucial segmental arteries, the clamps were released, and the patient was actively cooled to 32°C, thus affording additional neuroprotection. The aorta was then clamped again and opened. Patent segmental arteries were reattached and selectively perfused until the MEPs returned to baseline levels. When the aortic origin of the segmental artery supplying the Adamkiewicz artery was inside the cross-clamped area, this segmental artery was reattached and perfused first. In case MEP amplitudes remain adequate, we still reattached intercostal arteries but oversewed those that arose from a severely diseased aortic wall. The main reason for revascularizing these arteries despite adequate MEPs was based on our experience that initial, normal MEPs in the thoracic phase of the procedure might deteriorate during the abdominal phase. This is probably due to exclusion of the spinal cord blood supply through the lumbar arteries and pelvic circulation, and therefore, we anticipate this later cord ischemia by maximizing blood supply through the intercostals arteries.[15] When possible, revascularization of the internal iliac arteries was also performed.

Statistical analysis. Analysis on the relation between the number of patients for whom the MEPs declined or remained constant before corrective measures vs the presence or absence of collateral supply from outside the cross-

Table I. Preoperative results for collateral arteries in 55 patients[a]

Collateral supply	*Motor evoked potentials*	
	Decline	*Stable*
Absent, No (%)	9 (16)	15 (27)
Present, No (%)	1 (1.8)	30 (55)

Two-by-two table on the relation between the detection of collateral arteries (detected by magnetic resonance angiography) connecting to the Adamkiewicz artery and intraoperative spinal cord function determined by motor evoked potentials. Values represent the number of patients (No). Statistical significance by Fisher exact test: $P < .0015$.

clamped aortic region was performed by means of the Fisher exact test. For the subgroup of patients who underwent both preoperative and postoperative MRA, this analysis was repeated for the preoperative and postoperative situation. We also tested whether the change in the number of patients displaying collaterals before and after surgery was related to the decline of MEPs. Statistical significance was inferred at $P < .05$.

In addition, the positive- and negative-predictive values of the presence of collateral arteries on the intraoperative MEP declines were determined, which was considered as the "disease." Ideally, the presence of collateral arteries should accurately predict stable MEPs and thus should have a negative-predictive value of 100%. The positive-predictive value indicates to what extent the absence of collaterals predicts MEP declines.

RESULTS

Preoperative assessment. The Adamkiewicz artery was detected in all of the 85 patients and was separated from the anterior outlet vein (example in Fig 3). The Adamkiewicz artery originated from segmental arteries between the vertebral levels T8 and L2 and derived in 58 patients (68%) from the left side. Segmental arteries could be well identified in all patients, except for one patient where segmental arteries could not be discerned from the accompanying veins.

Table I lists patients in whom collateral supply, from outside the cross-clamped aorta, was observed and MEPs declined before surgical corrective measures. A significant ($P < .0015$) relation was found between presence of collaterals and intraoperative spinal cord function. Remote collaterals originated in most cases caudal to the distal clamp from the lumbar or pelvic arteries, or both (Figs 4, 5, and 6). The subgroup of 23 patients (63%) with advanced atherosclerosis had relatively more patients with collateral supply from outside the cross-clamped region than the nine patients (50%) in the dissection group, but this was not statistically significant ($P > .4$). Remote collateral supply came from either the pelvic or high-thoracic regions, or both (Figs 4, 5, and 6). Fig 7 shows an example of a patient in whom no collaterals were visualized.

The presence of collateral arteries predicted stable MEPs in 97% (ie, negative predictive value) of the patients, whereas absence of collateral arteries only predicted MEP decline in 37% (ie, positive predictive value) of the patients.

The connection between the Adamkiewicz artery and the aorta was through a direct segmental supply in 38 of the 55 patients (69%), whereas the remaining 17 patients (31%) had an indirect (ie, intersegmental collateral arterial) connection to a segmental artery located one or two levels higher or lower (example in Fig 4). The difference of the relative number of patients between the subgroup with advanced atherosclerotic disease (15 of 37; 41%) with an indirect segmental supply and the patients with a dissection (1 of 18; 6%) was statistically significant ($P < .01$).

Postoperative assessment. For the group of 21 patients who presented for a postoperative MRA, the Adamkiewicz artery and its segmental supply were identified at exactly the same vertebral level and side as before surgery. A similar relation was found between the preoperative identification of collaterals and intraoperative spinal cord function ($P < .01$) for these 21 patients as for the group of 55 patients. Table II relates the presence of collaterals for both the preoperative and postoperative situation to the stability of the MEPs. All patients displayed collateral supply after surgery, including those in whom no collaterals were detected before surgery. Also in five patients in whom no collaterals were preoperatively detected and MEPs remained stable, postoperative MRA revealed a well-developed collateral network (Fig 8).

Patient outcome. The flow chart in Fig 2 lists the four patients (4.7%) among the 85 total patients in the several TAA and TAAA groups in whom paraplegia manifested. In three patients (1 TAA, 1 type II TAAA, and 1 type III TAAA), acute paraplegia became evident after the procedure. This neurologic deficit was anticipated because MEPs were entirely absent at the end of the procedure. Sequential clamping of the thoracic and abdominal aorta was associated with a gradual decrease of MEPs to nonmeasurable amplitudes. Despite increasing mean arterial and distal aortic pressures and revascularizing all available segmental arteries, including the one supplying the Adamkiewicz artery, MEP signals did not return. No collaterals were found preoperatively in two of these three patients, and no patent segmental arteries for reattachment were available; and for one TAA patient, identification of collaterals was impossible owing to venous enhancement. In seven of the 10 patients in whom MEPs declined, the MEPs returned after reattachment of patent segmental arteries.

Delayed paraplegia occurred in one type II TAAA patient in whom exclusion of the entire aorta did not lead to a decline in MEPs. Owing to the very poor quality of the aorta and because no MEP declines were observed during the entire operation, no attempts were undertaken to revascularize any of the encountered back-bleeding segmental arteries, including the supplier of the Adamkiewicz artery. The patient had a short period of hypotension in the intensive care unit and thereafter was unable to move his legs. At the preoperative MRA, no collaterals were detected in this patient.

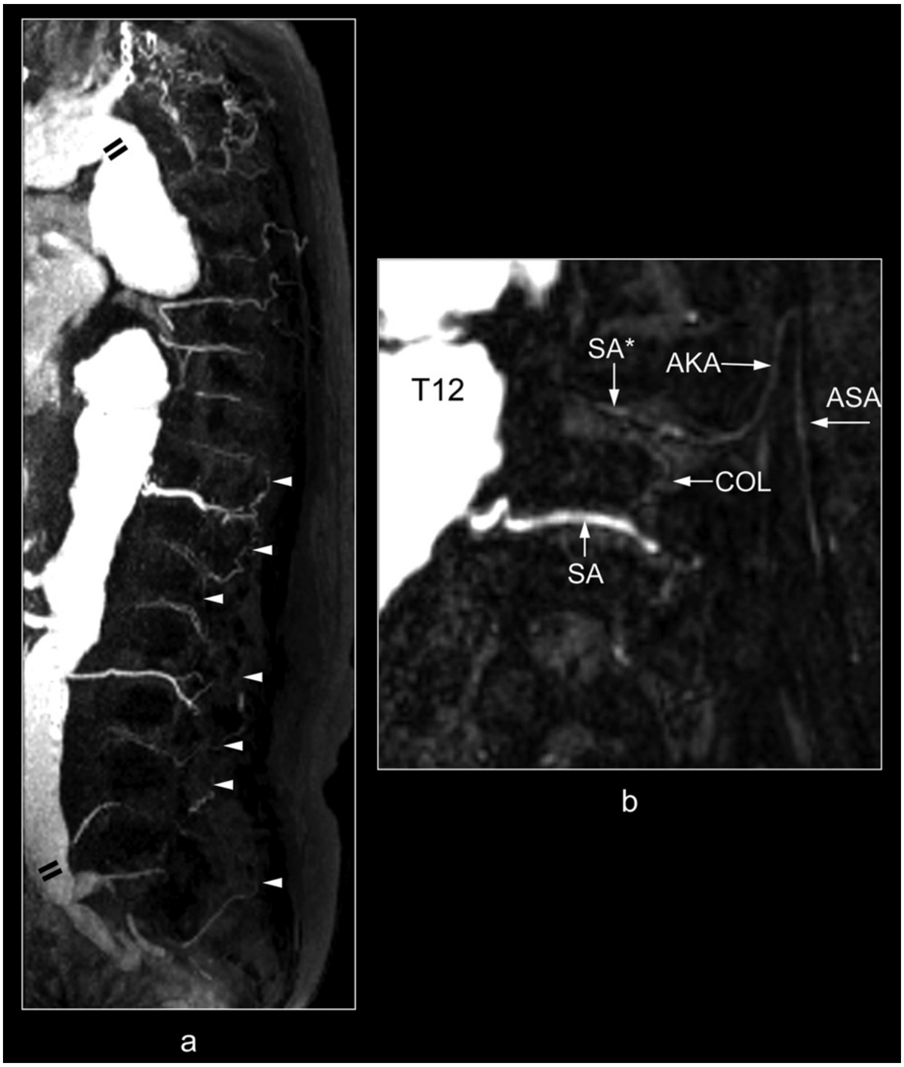


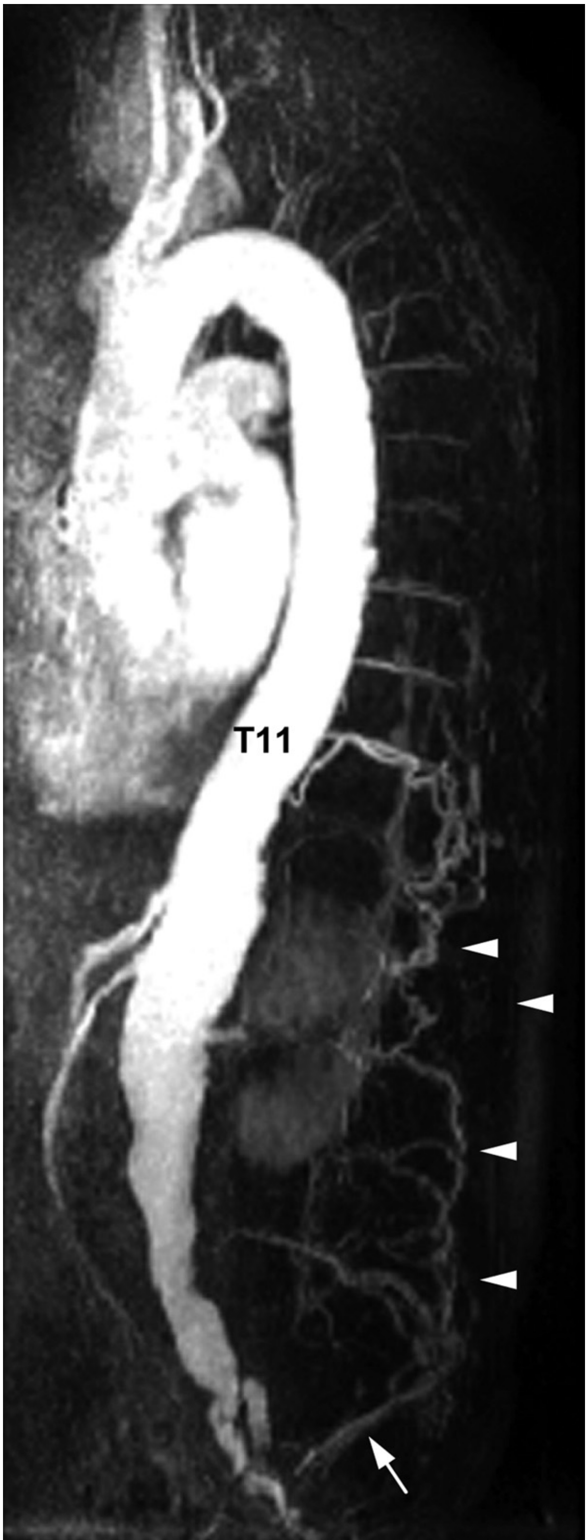
Fig 4. a, Preoperative contrast-enhanced magnetic resonance angiography of a 63-year-old woman with a type II thoracoabdominal aortic aneurysm shows that the collateral arteries arise from the pelvic region outside the cross-clamped aortic region *(double cross-bars)* and that the intersegmental collaterals *(arrowheads)* vertically interconnect the segmental arteries. **b,** This panel shows that the original direct segmental supply *(SA*)* to the Adamkiewicz artery *(AKA)* at T 12 and the anterior spinal artery *(ASA)* are partially occluded and that the segmental artery one level more caudally *(SA)* indirectly provides the blood supply.

DISCUSSION

Tailored preoperative planning in open TAAA surgery, and therefore, the intention of reducing neurologic complications, should ideally include the identification of all major patent blood-supplying trajectories to the spinal cord. These trajectories comprise the original direct intercostal or lumbar arterial as well as (potential) proximal and remote collateral supply. However in TAAA patients, preoperative imaging of collateral arteries is extremely challenging owing to their small calibers and variable origins.

When successful, intra-arterial catheter angiography provides the best image quality to visualize the existence and localization of the various arterial trajectories to the spinal cord[10] and could, therefore, be considered the preferred imaging modality. Despite this, catheter angiography is invasive, has limited and highly variable sensitivity (43% to 86%),[2,10] and has contraindications, including iodine allergy, severe renal impairment, and atherosclerotic plaques in aorta. The technique involves selective arterial catheterization, cannot visualize all arterial trajectories to the cord in one session, and furthermore, involves a small risk for iatrogenic paraplegia.[10]

In recent years, therefore, intensive efforts have been directed to the noninvasive imaging of the Adamkiewicz artery and its segmental supply with computed tomography or MRA.[6-8,13,14,16-20] So far, it remains unclear whether



the relevant collateral arterial trajectories, which expectedly have submillimeter- to millimeter-sized calibers, and their arterial origins can be visualized with noninvasive imaging techniques. Although the potential role of collateral circulation seems obvious, it has not been systematically imaged nor has investigation been done on whether its contribution is essential or just accessory.

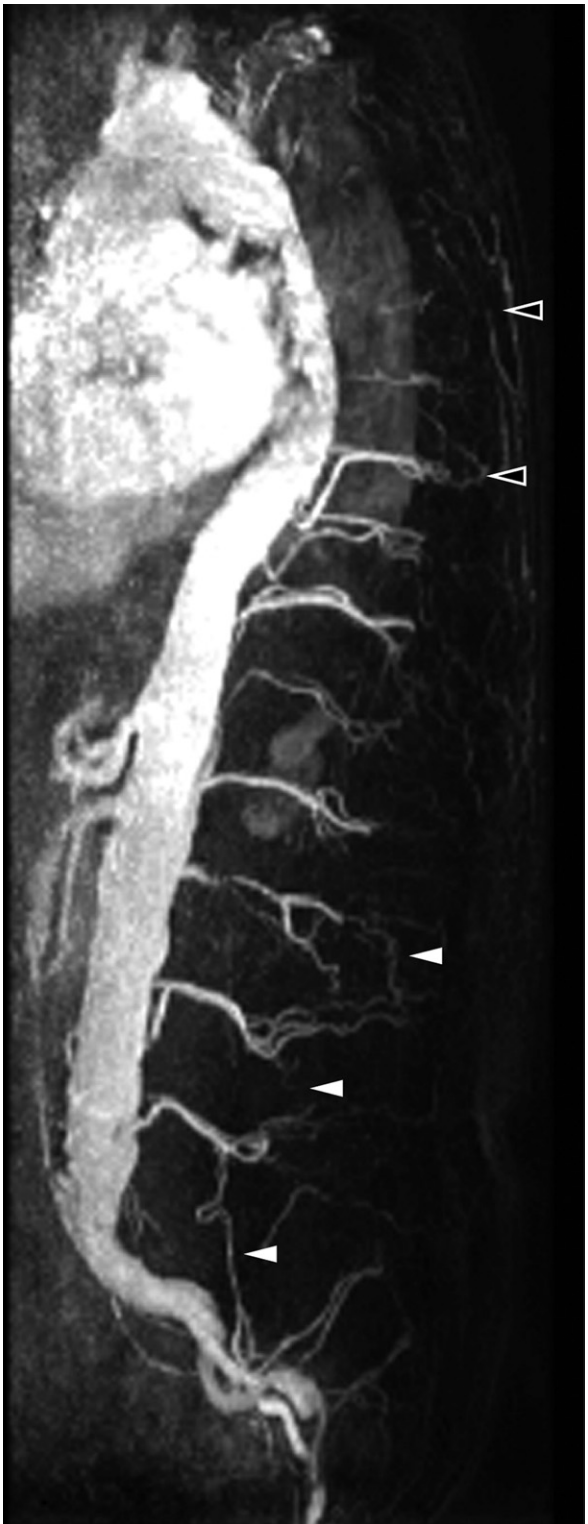
Current findings. Primarily, this study was initiated to determine whether MRA is able to preoperatively identify the collateral arterial routes that are potentially crucial for the blood supply to the spinal cord in TAA and TAAA patients. For the first time, to our knowledge, the collateral blood supply to the spinal cord was systematically visualized and its relation to the spinal cord function was investigated. Here a significant relation was found between the existence of the collateral arterial supply, originating from outside the cross-clamped aortic area, and the intraoperative spinal cord function before corrective measures during surgery. In case such a collateral arterial network was identified preoperatively, this had a 97% (negative) predictive value for stable intraoperative spinal cord function. Moreover, intraoperative declines of spinal cord function manifested in 38% (positive-predictive value) of the patients who did not display collaterals on MRA. This means that the remote collateral circulation adds crucially—and not just accessorily—to the spinal cord blood supply in TAA and TAAA patients. This phenomenon also emphasizes the important role of retrograde aortic perfusion during cross-clamping because lumbar and iliac arteries remain perfused during this phase of the procedure.

Second, we tested the hypothesis that when collateral arteries were relevant to the blood supply of the spinal cord, differences in collateralization should be observed before and after aortic repair. All patients that were imaged preoperatively and postoperatively, even those who preoperatively did not display collaterals, showed collateral arteries postoperatively with MRA. This was expected owing to the increase in blood flow in pre-existing collateral arteries, and therefore shear stress,[21] supplied by the remaining segmental or iliolumbar arteries.

Collateral trajectories. The failure to detect collateral arteries preoperatively does not mean that collateral circulation does not exist. Spatial resolution MRA might be too limited to show small pre-existing collateral networks. In 27% of the patients studied, in whom the segmental supply

Fig. 5. Preoperative contrast-enhanced magnetic resonance angiography of a 62-year-old man with a type III thoracoabdominal aortic aneurysm shows a well-developed network of collateral arteries *(arrowheads)* originating from the iliolumbar arteries *(arrow)*. Note that this remote collateral supply is the most dominant supply to the thoracolumbar spinal cord. Intraoperative motor-evoked potentials remained stable.

to the Adamkiewicz was excluded during surgery, no collateral arteries were detected and no intraoperative changes of the cord function were noticed. This observation would at first sight concur to the idea that alternative blood-supplying trajectories contribute to the (thoracolumbar) spinal cord other than through the Adamkiewicz artery. Additional trajectories that were found in autopsy studies[9] and catheter angiography[10] include the branches from the hypogastric arteries and subclavian artery and also transverse anastomoses from the posterior spinal arteries to the anterior spinal artery. These alternative trajectories were pointed out to connect to the anterior spinal artery. Because the corresponding vessel calibers may be smaller than the Adamkiewicz artery, these trajectories are likely too small before surgery to be detected with the current abilities of MRA. However, it seems unlikely that the blood supply by the alternative routes mentioned here is substantial during aortic cross-clamping or after surgery, because the proximal intersegmental and remote collateral circulation (ie, lumbar and pelvic) that connects to the Adamkiewicz artery appeared to have strongly developed in all patients studied. In line with this, it seems more likely that pre-existing collateral arteries dilate during aortic cross-clamping and oversewing of segmental artery orifices in the aortic wall. High blood pressure control and increased flow lead to the subsequent development of collaterals which conduct the required blood flow to the spinal cord. If, on the contrary, the blood supply through normal alternative trajectories (eg, posterior spinal cord arteries) would be sufficient in general, it would be unlikely that, particularly, the remote collateral circulation would develop as strong as observed in this study.



Advanced atherosclerosis versus dissection. For a substantial number of patients with advanced atherosclerotic disease, the segmental supply to the Adamkiewicz artery relied on intersegmental collateral connections compared with the group with aortic dissections. This is likely explained by the slow development of atherosclerotic plaque or thrombus over time that obstructs multiple segmental arteries, as has been shown in previous studies.[2,12,14] The relatively slow process of atherosclerosis also provides the time to allow maturation of proximal intersegmental collaterals. For dissection patients, however, the number of patent segmental arteries is known to be higher than for patients with advanced atherosclerotic disease; consequently, the necessity of intersegmental collaterals is less. But because the included chronic dissection patients displayed atherosclerosis to a moderate level as well, obstruction of segmental arteries manifests and the formation of remote collaterals was stimulated in a similar manner.

Relation to paraplegia. By using preoperative imaging of the arteries supplying the spinal cord, ideally one

Fig. 6. Preoperative contrast-enhanced magnetic resonance angiography of a 32-year-old man with a type II thoracoabdominal aortic aneurysm shows that well-developed collateral arteries originate from both the pelvic arteries *(white arrowheads)* and high thoracic regions *(open arrowheads)*. Intraoperative motor-evoked potentials remained stable.

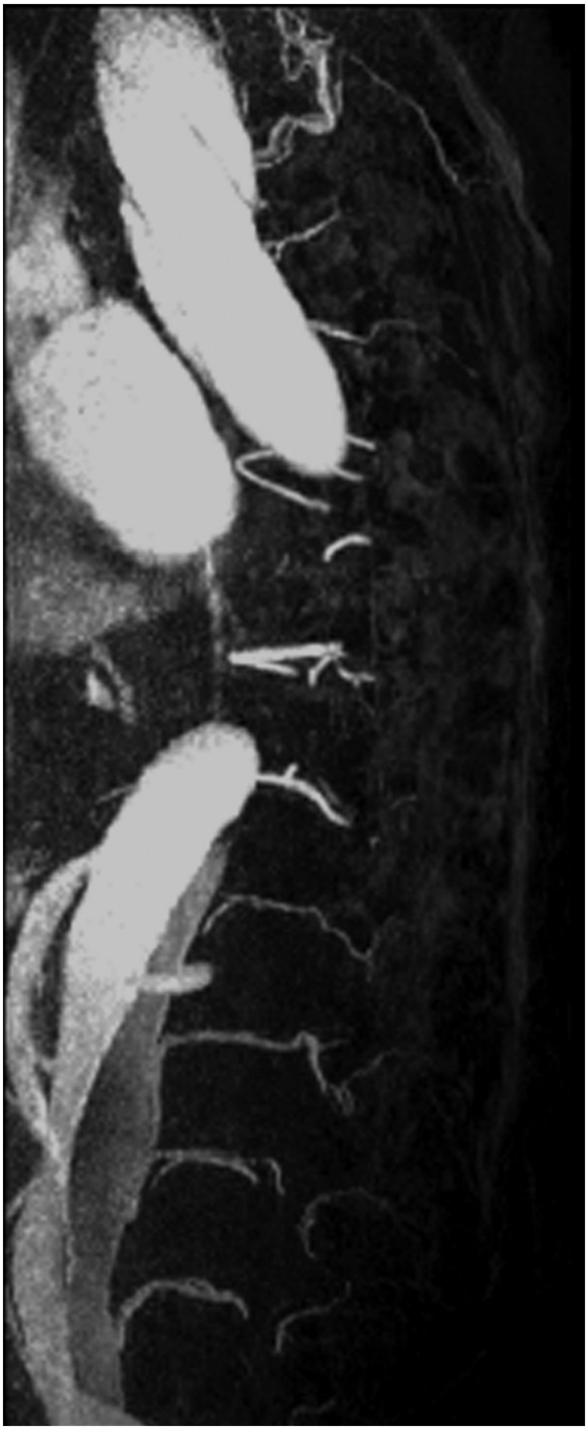


Fig 7. In this preoperative contrast-enhanced magnetic resonance angiography of a 58-year-old man with type II thoracoabdominal aortic aneurysm, no collateral arteries were identified. Intraoperative motor-evoked potentials declined during aortic cross-clamping but returned after selective revascularization.

Table II. Preoperative and postoperative functionality associated with declined or stable motor-evoked potentials for 21 patients with or without collaterals[a]

	Motor evoked potentials	
Collateral supply	*Decline*	*Stable*
Absent, No[b]	5 → 0	5 → 0
Present, No[b]	0 → 5	11 → 16

[a]Two-by-two table on the relation between intraoperative spinal cord function determined by motor evoked potentials and the detection of collateral arteries, determined by magnetic resonance angiography, connecting to the Adamkiewicz artery. All patients who had no collateral arteries preoperatively displayed collateral supply postoperatively.
[b]Preoperative number → postoperative number.

would like to observe a decrease in the number of incidences of paraplegia. One might argue that a limitation of this study was that the surgeon had no knowledge of the presence and trajectories of collateral supply as identified by MRA. Direct clinical application of information on collateral arteries was, however, beyond the aims of the current study.

It is remarkable that in three patients who became paraplegic, no collaterals could be identified preoperatively. This observation gives further support to the central idea that collaterals add to the protection of spinal cord function during aortic surgery. However, to explicitly obtain statistically significant results on the reduction of paraplegia incidences in future, or the relation between collateralization and paraplegia incidence, the number of patients to be included has to be much higher because the paraplegia rate is only a few percent. In the cases were the spinal blood supply will critically depend on collateral circulation, this emphasizes the need to keep blood pressure sufficiently high during and after the operation.

Sufficiency of collateral blood supply. In one of the 55 patients (1.8%), the MEPs diminished intraoperatively despite the preoperative identification of collateral arteries connecting to the Adamkiewicz artery. The exact explanation for this observation remains unclear because monitoring did not reveal hypotensive periods. Phenomena not related to insufficient hemodynamic adaptations, such as an embolus, may have occluded the intraoperative blood supply. This raises the notion that although we are able to identify and localize collateral arteries, uncertainty remains about whether this represents a blood supply that is functionally sufficient for the spinal cord in all cases. In 30 of 31 patients, the preoperatively identified collateral supply appeared to be sufficient to maintain the spinal cord function.

An intrinsic limitation of MRA is that it provides vascular anatomic information but not functional information in the form of quantitative blood flow. To predict whether collateral blood supply is indeed functionally sufficient would require quantitative MR perfusion or flow techniques, or both, which up to now have not been realized for such small vessels. The eventual preoperative application of such techniques would further still be complicated by the

Fig 8. **a,** Preoperative contrast-enhanced magnetic resonance angiography (MRA) of a 46-year-old man with a type II thoracoabdominal aortic aneurysm. **b,** The postoperative MRA shows strong development of the remote collateral arterial supply from the pelvic region after aortic repair. Intraoperative motor-evoked potentials remained stable.

fact that the intraoperative flow in such collateral arteries may be substantially higher than in the preoperative situation.

Clinical perspective. We believe that preoperative MRA strongly adds to the identification of patients that are at increased risk for spinal cord dysfunction. The likelihood that intraoperative spinal cord dysfunction will manifest is much lower in patients who display collateral supply (3%) at preoperative MRA than in those who do not (38%). Collateral supply found in this study appeared to be highly predictive (97%) for stable spinal cord function. This means that patients who do not preoperatively display collaterals are at increased risk for developing temporary or permanent spinal cord dysfunction, or both, in open and endovascular repair.

We also believe that particularly those surgery programs that do not have access to intraoperative MEP monitoring would benefit from preoperative identification of the Adamkiewicz artery[6] and the identification of collateral networks. The current study suggests that a predictive relation exists between preoperative vascular anatomy and the patient's intraoperative hemodynamic situation. Using the preoperative vascular anatomic information could potentially change the surgical strategy to minimize the potential incidence of ischemic spinal cord injury and identify patients who have an increased risk for developing paraplegia. Future studies are needed to demonstrate its clinical value in reducing incidences of paraplegia.

CONCLUSIONS

The current study shows that MRA is able to visualize the original anatomic as well as collateral blood supply to the spinal cord in preoperative TAA and TAAA patients. The preoperative identification of collateral arteries was highly predictive for stable intraoperative spinal cord function. When collaterals are present, MEP declines are unlikely. The ability to predict affirmative changes in MEP based on collateralization is, however, more limited. During and after aortic aneurysm repair, the spinal cord blood supply may crucially depend on collateral arteries. Pre-existing collateral trajectories seem to dilate in response to the modified hemodynamic situation during aortic aneurysm repair. Moreover, by using MRA for presurgical evaluation, one should be able to determine which patients are at increased risk for developing spinal cord dysfunction during, and expectedly after, aortic aneurysm repair.

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AUTHOR CONTRIBUTIONS

Conception and design: WB, RN, MJ
Analysis and interpretation: WB, RN, FW
Data collection: RN, WM, GS, MJ
Writing the article: WB, WM, MJ
Critical revision of the article: WB, MJ
Final approval of the article: WB, MJ
Statistical analysis: WB, RN, FW
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Overall responsibility: WB

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